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TECHNICAL SPECIFICATION

colour inside

Solar thermal electric plants –
Part 2-1: Thermal energy storage systems – Characterization of active, sensible systems for direct and indirect configurations

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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SOLAR THERMAL ELECTRIC PLANTS –

Part 2-1: Thermal energy storage systems – Characterization of active, sensible systems for direct and indirect configurations

FOREWORD

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IEC TS 62862-2-1 has been prepared by IEC technical committee 117: Solar thermal electric plants. It is a Technical Specification.

The text of this Technical Specification is based on the following documents:

Draft TS	Report on voting
117/119/DTS	117/127/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 62862 series, published under the general title *Solar thermal electric plants*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

IEC TC 117 prepares International Standards (and other types of documents) for systems of solar thermal electric (STE) plants for the conversion of solar thermal energy into electrical energy and for all the elements (including all sub-systems and components) in the entire STE energy system. These documents would cover all current different types of systems in the STE field, as follows:

- Parabolic trough
- Solar tower
- Linear fresnel collectors
- Parabolic dish
- Any other type of system using thermal storage that is not connected to the grid.

The documents define terminology, design and installation requirements, performance measurement techniques and test methods, safety requirements, and "power quality" issues for each of the above systems.

In addition to those systems, there are several major components that require standardization, such as the storage media (oil, molten salt, ceramic, concrete, etc.).

SOLAR THERMAL ELECTRIC PLANTS –

**Part 2-1: Thermal energy storage systems –
Characterization of active, sensible systems for
direct and indirect configurations**

1 Scope

This document defines the requirements and the test methods for the characterization of thermal energy storage (TES) systems.

This document contains the information necessary for determining the performance and functional characteristics of active direct and indirect thermal energy storage systems based on sensible heat in solar thermal power plants using parabolic-trough collector, Fresnel collector or tower central receiver technology with liquid storage media.

This document includes characterization procedures for testing energy storage system charge and discharge, as well as reporting the results. Test performance requirements are given and the instrumentation necessary for them, as well as data acquisition and processing methods and methods for calculating the results and their uncertainties.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TS 62862-1-1:2018, *Solar thermal electric plants – Part 1-1: Terminology*

IEC 60584-1:2013, *Thermocouples – Part 1: EMF specifications and tolerances*

IEC 60751:2008, *Industrial platinum resistance thermometers and platinum temperature sensors*

ISO 5725-3, *Accuracy (trueness and precision) of measurement methods and results – Part 3: Intermediate measures of the precision of a standard measurement method*

ISO 5725-6, *Accuracy (trueness and precision) of measurement methods and results – Part 6: Use in practice of accuracy values*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 62862-1-1 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

4 Symbols and abbreviated terms

The symbols, units, subscripts, superscripts, and abbreviated terms shown in Table 1 and Table 2 are used in this document.

Table 1 – List of symbols and units

Name	Symbol	Units	Observations
Confidence level		%	
Coverage factor	FC	-	dimensionless
Critical range factor	$f(n)$	-	dimensionless
Energy	E	J or Wh	
Mass flow rate	$\dot{m}$	kg/s	
Performance	η	%	
Power	P	W	
Storage capacity	φ	J or Wh	
Storage level		%	
Temperature	T	°C or K	
Time	t	s	
Uncertainty	s		The units are those of the variable to which the uncertainty refers
Velocity	v	m/s	
Volumetric flow rate	$\dot{V}$ or Q	m^3/s	

Table 2 – List of subscripts, superscripts and abbreviated terms

Script	Meaning
*	Instantaneous value
AMB	Ambient
C	Charge
D	Discharge
DCS	Distributed control system
E	Electrical
HTF	Heat transfer fluid
i, j, k	Numbering value
IN	Inlet
OUT	Outlet
M, N	Number of data recorded or representative
MSF	Molten salt fluid
Q	Flow meter number
RTD	Resistance temperature detector
T	Thermal
TES	Thermal energy storage

5 Thermal energy storage (TES) systems

5.1 Classification of TES systems

Thermal storage can be classified according to several different criteria:

- Thermal energy storage mode: thermal energy supplied by the solar field may be stored as sensible heat, latent heat, reaction heat or a combination of them.
- Circulation of the storage medium: TES systems can be classified as active or passive.
- System configuration: thermal energy storage systems may be direct or indirect.

For more details regarding the types of TES systems, refer to Annex A.

5.2 TES systems covered by this document

This document covers active sensible two-tank direct and indirect thermal storage systems using "molten salt"[1] as the storage media. The term "molten salt" shall be considered synonymous with "solar salt" in any part of this document. Furthermore, in the case of direct storage, molten salts are also used as the HTF.

5.3 TES system limits

The boundary limits of the different TES systems covered in this document are described below.

In the case of indirect systems:

a) the limit is the inlet at the HTF side of the heat exchanger between the HTF and molten salt.

b) the limit is the outlet at the HTF side of the heat exchanger between the HTF and molten salt.

In the case of direct systems:

c) the limit is the inlet side of the TES: the inlet at the cold tank and the inlet at the hot tank.

d) the limit is the outlet side of the TES: the outlet at the cold tank and the outlet at the hot tank, when discharging the TES.

Refer to 7.4 for the system boundaries diagrams.

5.4 Key components

All the following types of equipment, at a minimum, are considered as key components of the thermal energy storage system:

- storage medium,
- storage tanks,
- piping,
- heat exchangers (in the case of indirect storage systems),
- electrical system,
- control systems,
- safety systems,
- pumps and valves,
- instrumentation: pressure gauges, thermocouples, flow meters, level gauges.

[1] The description of "molten salt" is provided in Annex B.

For more details regarding the components of a TES system, refer to Annex B.

The documentation that should be provided by the TES manufacturer/supplier is given in Annex D.

6 Instrumentation and measurement methods

6.1 General

The following measurements in this Clause 6 shall be taken and recorded during testing.

6.2 Flow rate measurements

The flow meter to be used for the flow rate measurement should provide Type B uncertainty below 1 % in flow rate measurements within the heat transfer fluid working temperature range.

During instrument installation, special attention should be given to all the requirements for ensuring proper equipment functioning (e.g., respecting the length of straight sections upstream and downstream from the flow meter, what direction the sensor should be facing, etc.), which shall be defined by the supplier.

When the flow meter measures the volumetric flow rate in m^3/s, the density of the heat transfer fluid, which is a function of temperature, shall be calculated. For this, a temperature sensor is installed as close as possible to the flow meter, but without preventing it from working properly.

The instantaneous volumetric flow rate of the heat transfer fluid $\dot{V}$ or Q^* which feeds the storage system in time t is measured in m^3/s.

For reliable measurement, at least two independent flow meters are required, located at the inlet and outlet of the storage system. Furthermore, the minimal installation conditions required by the manufacturer should be respected.

Flow rate measurement treatment shall be performed according to Clause C.1.

6.3 Temperature measurements

6.3.1 Heat transfer fluid temperatures

The instantaneous temperatures of the heat transfer fluid are measured at time t, at a maximum distance of 5 m from the inlet or outlet of the test boundary. If this is not possible, they are measured at the closest point to the inlet or outlet of the test boundary. These temperatures may be given by any temperature measurement device, thermocouple or RTD, as long as the sensor part of the device is well within the fluid and is resistant to its contact, or, alternatively, the sensor is within the thermowell, and is also well within the fluid and is in contact with the inner wall which enables it to be read correctly. For long connection lengths to the measurement point, an analogical-digital conversion protocol is recommended.

Instantaneous data shall be recorded by the data acquisition system for a period of less than 1 min. At least three independent sensors are required at the inlet and as many at the outlet, so there are at least the required number of instantaneous data series detailed in Clause C.2.

The uncertainties considered in the measurement are those of the measurement sensor, extension and compensating cables, and the data acquisition system device. In the case of thermocouples, the uncertainties shall be of Class 1 in accordance with IEC 60584-1 and Class A in accordance with IEC 60751 for RTDs.

6.3.2 Wall temperatures

Temperature measurements of the external wall of insulation of the hot and cold tank shall be performed to monitor that the external surface temperature does not exceed 55 °C.

The instantaneous temperatures of the external wall are measured continuously at four equidistant points around the tank circumference at least at two different elevations.

The lower elevation shall be at 1,5 m above the platform where the tank is erected. The higher elevation corresponds to the centre of the band that comprises the ¾ portion of the tank height.

These temperatures may be given by any temperature measurement device, thermocouple or RTD.

Instantaneous data shall be recorded by the data acquisition system for a period of less than 1 h.

The uncertainties considered in the measurement are those of the measurement sensor, extension and compensating cables, and the data acquisition system device, that is, Type B uncertainties. The maximum Type B uncertainty allowed in transfer flow temperature is ±1,5 °C.

6.4 Level measurements

The instantaneous level of the heat storage fluid in the hot tank shall be measured continuously. These levels may be given by any continuous level sensors, as long as the sensor part of the device is suitable as regards the fluid and the physical characteristics of the fluid.

Any maximum deviation with respect to nominal values shall be agreed upon by the parties and included in the test procedure. Instantaneous data shall be recorded by the data acquisition system for a period of less than 1 min. At least two independent sensors are required in the hot tank.

The uncertainties considered in the measurement are those of the measurement sensor and the device, that is, Type B uncertainties. The maximum Type B uncertainty allowed in level measurement is ±0,1 m.

6.5 Meteorological signal measurements

6.5.1 Wind speed and direction

Since wind speed and direction affect storage system thermal losses, they shall be measured during testing to determine storage system overall energy and thermal losses. Wind speed is measured by anemometers located at a height no lower than 10 m from the ground, and outside of the range of disturbances caused by adjacent elements. These sensors shall have an uncertainty of ±0,5 m/s or less. If there are several anemometers, the measurement nearest the storage system shall be taken as valid for each record.

For each anemometer, 1 s records shall be used to calculate the mean wind speed during a recording interval of no longer than 10 min.

These measured data records shall be included in the test report and shall be processed as defined in the test procedure.

6.5.2 Ambient temperature

This measurement is only necessary in tests for calculating storage system overall energy and thermal losses.

Maximum Type B uncertainty associated with ambient temperature data recorded by the data acquisition system shall be ±1 °C.

Ambient temperature shall be measured at a position near the storage system, with the sensor protected from nearby heat sources, such as direct solar radiation. It should be especially verified that the sensor position is not within the field of hot air currents caused by gas or vapour emitted by nearby equipment.

The measured data recorded shall be included in the test report and shall be processed as defined in the test procedure.

6.6 Data acquisition

All measured signals shall be (i) recorded by a computer controlled data acquisition system that shall be connected to the DCS of the power plant and (ii) verified with visual readings.

In some extreme conditions where it is not possible to install a temporary computer controlled data acquisition system, data may be recorded manually in suitable form sheets with date and time.

During the test period and when not specified otherwise:

1) the measurements automatically recorded on a computer shall be taken instantaneously, meaning at least every 30 s, and
2) any data collected in writing shall be recorded on data sheets not less than six (6) times per hour, except for flow measurements, which shall be carried out and recorded not less than twelve (12) times per hour. Ambient and wall temperatures should be measured once every hour.

The data collection system shall be designed to:

a) comprise multiple instrument outputs,
e) gather all the necessary data simultaneously, meaning within a maximum interval of 5 s,
f) run any necessary calculations with data collected at the same time, and
g) store data and simulation results.

At all representative operating conditions during each test run, all the DCS screens (showing pressures, temperatures, flows, power, operating status, etc.) shall be printed for inclusion in the test report appendices.

Data collected by temporary test instruments shall be recorded in a dedicated collection system.

All test data (raw and processed data) shall be available.

7 General requirements on tests

7.1 General

Some general requirements for thermal energy storage system characterization testing are defined.

7.2 Test procedure

7.2.1 General

A detailed document about the test plan called the test procedure shall be prepared and approved by the parties involved before testing. This basic document shall include all the details for preparing and performing the tests, as well as calculating and presenting the results. The document shall include two groups of points agreed by the parties: those points which are required and those which are optional.

7.2.2 Items to be included in the test procedure

The test procedure shall include at least the following:

1) Description of the thermal energy storage system, operating modes, nominal heat transfer fluid conditions during storage tank charge and discharge, nominal storage capacity, nominal cold tank temperature, nominal hot tank temperature, storage hours, thermal performance and full charge and discharge times.
2) Definition of the 0 % and 100 % storage level indicating the hot tank and cold tank levels and temperatures.
3) Thermal energy storage system boundary, identifying measurement points.
4) Exhaustive list of measurement instruments and equipment, describing coding, calibration, location, amount, type, uncertainty and main technical data. The instrumentation to be used for testing shall comply with specifications in Clause 6. All the measurement equipment necessary, both permanent instruments installed in the plant and any temporary instruments shall be checked, inspected and adjusted before beginning testing.
5) Calibration certificates for the instruments listed.
6) Heat transfer fluid and storage medium properties as a function of the working temperature.
7) Purpose of testing, indicating how long tests are supposed to take.
8) Definition of the reference test conditions for the site shall include ambient temperature, relative humidity, wind speed, elevation, atmospheric pressure, etc. The values of these reference test conditions shall be the same as the design conditions which may be corrected with the adequate provided correction curves.
9) Basic test plans: the test conditions shall at no time exceed the maximum limitations of equipment involved as stated by the supplier, or normal plant operating procedures.
10) Definition of any acceptable maximum deviations from values given in the test plan.
11) Data recording and processing shall be in accordance with specifications in Clause 6. The procedure to be followed in case of discrepancies in data recorded for a same physical quantity.
12) Confidence level, and therefore, coverage factor, for calculating expanded uncertainty of different characteristic parameters.
13) Wind speed and direction and ambient temperature data processing.
14) Test result evaluation method. Parameters to be verified, along with their guaranteed values and/or system reference, and criteria for comparison, if applicable.
15) Definition of correction factors applicable to the results when there are deviations between nominal values and those measured during testing.

7.2.3 Items to be agreed between the parties

If the parties involved deem it so advisable, they may exclude some of the following recommendations from the test procedure:

1) Reference to plant operating methods, including primary and auxiliary equipment which could affect the test results.
2) Sampling, preparation and analysis methods for heat transfer fluid and storage medium and/or substances related to the non-solar energy supply, if any, indicating how and with what frequency their properties are measured or calculated.
3) Identification of the laboratory that analyses the heat transfer fluid and storage medium and/or substances related to the non-solar energy supply, if any.

4) Description of activities to be performed during preparation of the test, such as verification of measurement equipment, training of personnel taking part in the test or any preliminary testing.

5) Detailed description of activities to be performed during testing, such as checking conditions for starting and ending the test, operating method, adjustments permitted before and after the test and data acquisition.

6) Data acceptance and rejection criteria. If the data acquisition system should fail and there are gaps in the data, it shall be agreed how to complete the data or what time interval without data is considered not to affect the final result.

7) Procedure for data distribution. The measured data shall be stored in files that shall be made available to the interested parties. Processing and calculations derived from these data shall be performed in different files from the original measurements, and a final report on results shall be written giving the explicit results of the tests.

8) Specific reference to the simulation model used to find the guarantee values and its description.

9) Procedure for determining the effect of thermal energy storage system component degradation.

10) Test to determine overall thermal energy storage system losses.

11) Other tests not described in this document.

7.3 Definition of the test included in this document

7.3.1 General

A preliminary test should be performed to check that the plant is in condition to start testing, that the measurement equipment and data acquisition systems are working properly, that the expected uncertainty in the result is acceptable, and that the worksheet and model show the algorithms described in the procedure. It should be a short test, for example two hours long, before starting storage system testing.

Calibration reports and working conditions of all the instrumentation used shall be adequate. After testing, only of those instruments suspected of malfunctioning should be verified for adequate working condition and calibration reports.

Besides the following types of tests that shall be performed, the wall temperature as well as the status of storage for the TES system shall be monitored.

7.3.2 Test to determine the thermal efficiency of the storage system

This test consists of charging the thermal energy storage system from a 0 % initial state to 100 % and discharging it immediately afterwards to 0 %, recording the variables given in Clause 6 for determining thermal performance of the thermal energy storage system. During both charging and discharging, the measurements shall be very near nominal conditions. Any maximum deviation with respect to nominal values shall be agreed upon by the parties in the test procedure. The entire test shall be performed without any external energy supply, except for what is necessary to ensure safe functioning of the storage system.

7.3.3 Test to determine the heat capacity of the storage system

The variables recorded and described in Clause 6 may be used to determine the storage system capacity, or a similar test may be done, that is, starting out with the storage system fully charged (100 %) it is fully discharged immediately afterwards, recording the variables given in Clause 6. During discharging, the measurements shall be very near nominal conditions. Any maximum deviation with respect to nominal values shall be agreed upon by the parties in the test procedure. The entire test shall be performed without any external energy supply, except for what is necessary to ensure safe functioning of the storage system.

7.3.4 Test to determine the thermal losses of the storage system

Storage system thermal losses shall be determined by the difference between the energy discharged by the storage system immediately after having reached full charge of 100 % and the energy discharged by it after the agreed test duration between charge and discharge defined in the test procedure. In this test, two scenarios related to the same operating mode, the storage system discharge mode, are compared.

The agreed duration between the two charges should not exceed 25 h and the entire test shall be done without any external energy supply, except for what is necessary to ensure safe functioning of the storage system. See Figure 1 for the agreed duration between two charges.

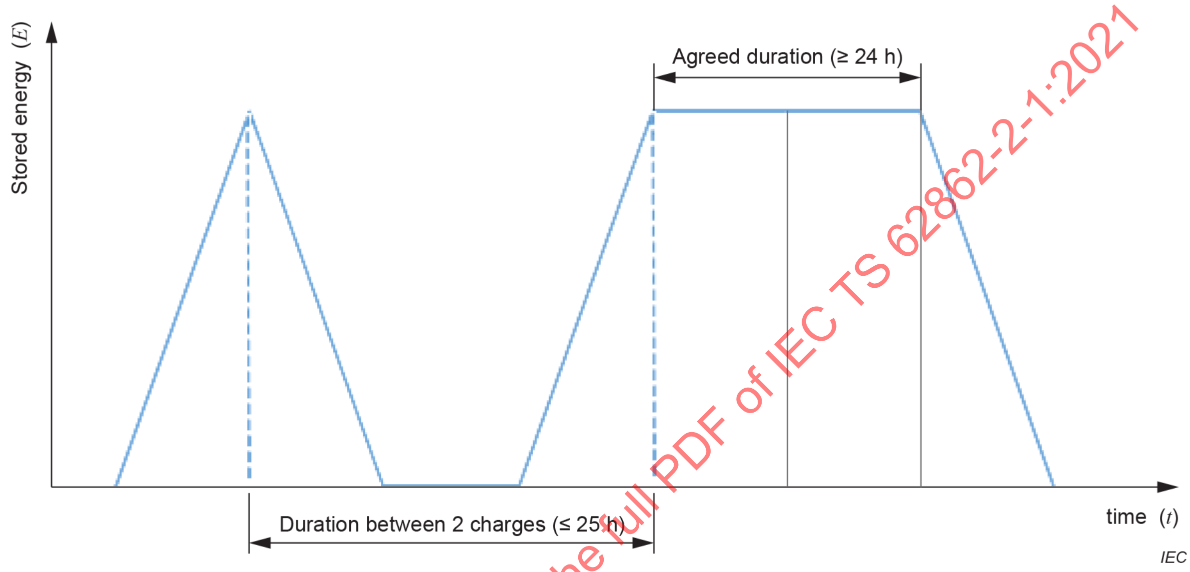


Figure 1 – Agreed duration between two charges

7.3.5 Test to determine the global losses of the storage system

The overall energy loss from the storage system shall be determined by the difference between the energy transferred to the system during full charge (100 %) and the total energy it delivers, when the duration defined in the test procedure has passed. In this test, two scenarios related to different storage system operating modes, the charge and discharge modes, are compared. These scenarios may be the scenarios described in 7.2.3 or any other scenarios agreed between the parties.

The entire test shall be done without any external energy supply, except for what is necessary to ensure safe functioning of the storage system.

7.3.6 Test to determine the wall temperature

The wall temperature shall be determined to ensure the safety of the operators and to verify that the thermal losses are minimized.

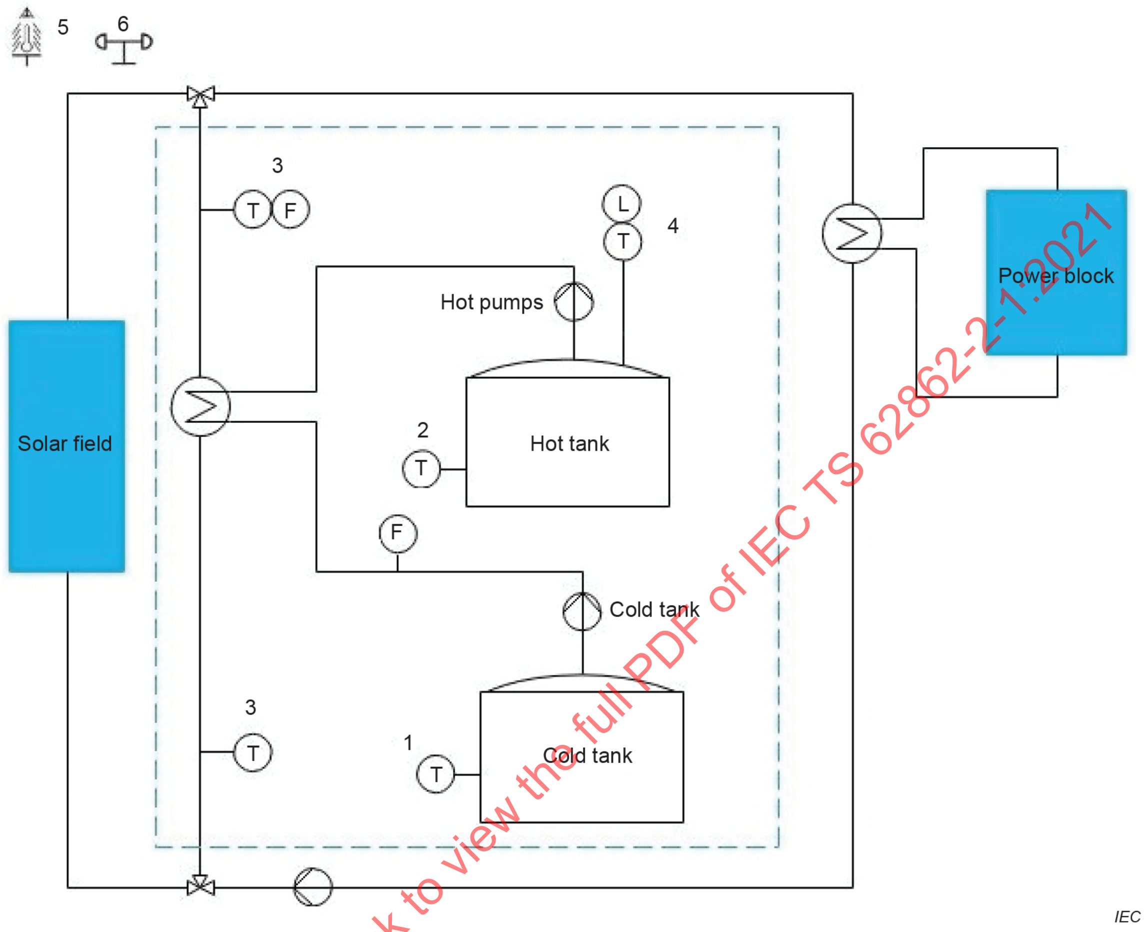
Temperature measurements of the external wall of the hot and cold tank shall be performed as detailed in 6.3.2.

The wall temperature may be:

- monitored continuously and recorded in the data acquisition system, and/or
- measured at least twice a year (one test every 6 months).

7.4 Test boundaries

Figure 2 shows a general typical diagram of the system and test boundaries for indirect TES systems.



Key

1 Temperature sensor to measure the external temperature of the cold tank wall

2 Temperature sensor to measure the external temperature of the hot tank wall

3 Temperature sensor to measure the inlet/outlet temperatures
Flowmeter to measure the flow in charge/discharge mode to be located in the cold or hot side

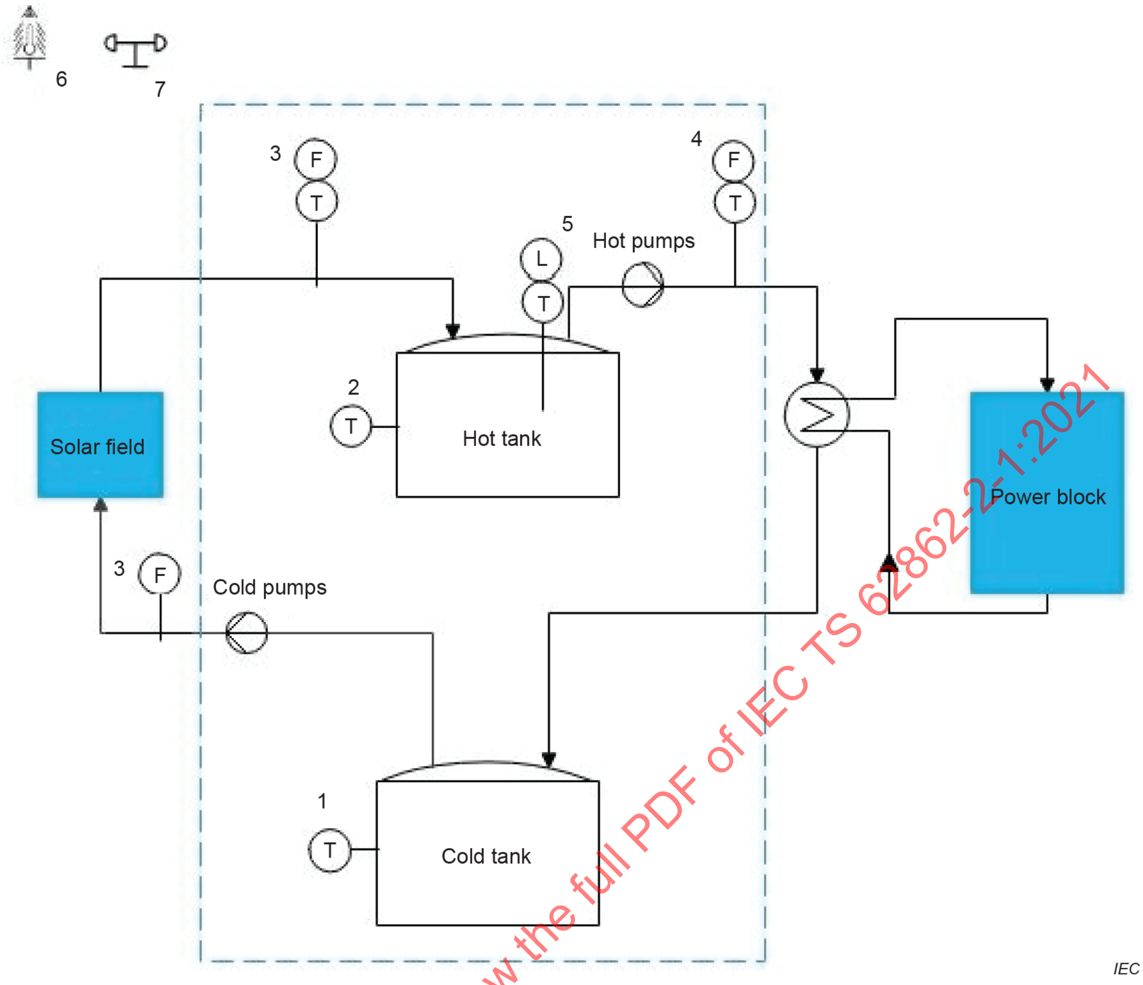
4 Level sensor to measure the volume into the hot tank
Temperature sensor to measure the temperature in the hot tank

5 Ambient temperature sensor

6 Anemometer

Figure 2 – General typical diagram of the system and test boundaries for indirect TES systems

Figure 3 shows a general typical diagram of the system and test boundaries for direct TES systems.



Key

1 Temperature sensor to measure the external temperature of the cold tank wall

2 Temperature sensor to measure the external temperature of the hot tank wall

3 Temperature sensor to measure the inlet temperature
Flowmeter to measure the flow in charge mode

4 Temperature sensor to measure the outlet temperature
Flowmeter to measure the flow in discharge mode

5 Level sensor to measure the volume into the hot tank
Temperature sensor to measure the temperature in the hot tank

6 Ambient temperature sensor

7 Anemometer

Figure 3 – General typical diagram of the system and test boundaries for direct TES systems

8 Storage system characterization (storage thermal performance and capacity)

8.1 Thermal efficiency and storage capacity (storage thermal performance and capacity)

8.1.1 Test methodology

The test for determining storage system thermal performance and effective capacity requires 100 % charge and immediately afterward discharge down to 0 %. During testing there shall not be any external thermal energy supply (trace heating, heating elements, boilers, etc.), except what is necessary to ensure safe functioning of the storage system. The test consists of several stages which are described below.

1) Starting out from the fully discharged (0 % storage) storage system, it is fully charged (100 % storage), and the nominal temperature and volume associated with the hot tank are reached at the end of charging. Any maximum deviation with respect to the nominal values shall be agreed by the parties in the test procedure. Before charging, it is recommended that the entire storage system be preheated to a temperature as close as possible to the one specified in the operating procedures, and this situation shall be verified by measuring the temperature at various points in the system. These various points shall be at least the points described in 6.2.
2) The thermal energy supplied to the system during this full charge, E_{C}, is determined.
3) Immediately afterwards, the storage system is fully discharged in an associated time $t_{\text{full discharge}}$, recording the variables detailed in Clause 6.
4) The thermal energy supplied by the system during this full discharge (effective capacity expressed in J, ($\varphi|_{\text{J}}$)) is determined.

8.1.2 Calculation procedure

From the series of results $\left\{T_k^{\text{in}}\left(s_k^{\text{in}}\right)\right\}$, $\left\{T_k^{\text{out}}\left(s_k^{\text{out}}\right)\right\}$ and $\left\{q_k\left(s_{q,i}\right)\right\}$ or $\left\{m_k\left(s_{m,k}\right)\right\}$ found according to the instructions in Clause 7, and from the functions for the physical properties (specific heat, $c_p\left(T\right)\left(s_{c_p(T)}\right)$, and density, $\rho\left(T\right)\left(s_{\rho(T)}\right)$) the series of results associated with power, $\left\{P_k\left(s_{P,k}\right)\right\}$, can be found. The data for $c_p(T)$ and $\rho(T)$ and their corresponding uncertainties shall be found directly from existing analysis of fluid samples supplied by a laboratory recognised by both parties. The power supplied to the storage system during charge $\left\{P_k^{\text{C}}\left(s_{P,k}\right)\right\}$ or by the storage system during discharge, $\left\{P_k^{\text{D}}\left(s_{P,k}\right)\right\}$, can be calculated using the following procedure (calculation of associated uncertainties is based on ISO/IEC Guide 98-3):

- If volumetric flow meters are used, $\left\{q_k^{\text{C}}\left(s_{P,k}\right)\right\}$, $\left\{q_k^{\text{D}}\left(s_{P,k}\right)\right\}$:

For indirect TES, a sole volumetric flowmeter, q, is used for charge and discharge:

$$P_k^{\text{C}} = P_k^{\text{D}} = q_k \rho\left(T_{q,k}\right)\left|h(T_k^{\text{in}}) - h\left(T_k^{\text{out}}\right)\right| \tag{1}$$

The fluid enthalpies at the inlet ($h(T_k^{\text{in}})$) and outlet ($h(T_k^{\text{out}})$) are determined according to the procedure described in Annex E, 7.1.2. If the fluid enthalpies are unknown, the according powers at the inlet and outlet can be determined using the specific heat capacity of the fluid according to:

$$P_k^{\text{C}} = P_k^{\text{D}} = q_k \rho\left(T_{q,k}\right) c_p\left(T_k\right)\left|T_k^{\text{in}} - T_k^{\text{out}}\right| \tag{2}$$

If the fluid enthalpies are unknown, the uncertainty of the specific heat capacity shall be considered appropriately.

For direct TES:

$$P_k^{\text{C}} = q_k^{\text{C}} \rho\left(T_{q,k}\right)\left|h(T_k^{\text{in}}) - h(T_k^{\text{cold nom}})\right| \tag{3}$$

$$P_k^{\mathrm{D}} = q_k^{\mathrm{D}} \rho\left(T_{q,k}\right)\left|h(T_k^{\mathrm{out}}) - h(T_k^{\mathrm{cold\ nom}})\right| \tag{4}$$

The salt enthalpies at the inlet ($h(T_k^{\mathrm{in}})$) and outlet ($h(T_k^{\mathrm{out}})$) are determined according to the procedure described in Annex E, 7.1.4. If the salt enthalpies are unknown, the relevant powers at the inlet and outlet can be determined using the specific heat capacity of the salt according to:

$$P_k^{\mathrm{C}} = q_k^{\mathrm{C}} \rho\left(T_{q,k}\right) c_p\left(T_k\right)\left|T_k^{\mathrm{in}} - T_k^{\mathrm{cold\ nom}}\right| \tag{5}$$

$$P_k^{\mathrm{D}} = q_k^{\mathrm{D}} \rho\left(T_{q,k}\right) c_p\left(T_k\right)\left|T_k^{\mathrm{out}} - T_k^{\mathrm{cold\ nom}}\right| \tag{6}$$

If the salt enthalpies are unknown, the uncertainty of the specific heat capacity shall be considered appropriately, where $T_{q,k}$ is the representative temperature near the flow meters and T_k is the average of T_k^{in} and T_k^{out}, that is $T_k = \frac{1}{2}\left(T_k^{\mathrm{in}} + T_k^{\mathrm{out}}\right)$;

$$s_{P,k} = P_k \sqrt{\left(\frac{s_{q,k}}{q_k}\right)^2 + \left(\frac{s_{\rho}\left(T_{c,k}\right)}{\rho\left(T_{c,k}\right)}\right)^2 + \left(\frac{s_{c_p}\left(T_k\right)}{c_p\left(T_k\right)}\right)^2 + \frac{\left(s_k^{\mathrm{in}}\right)^2 + \left(s_k^{\mathrm{out}}\right)^2}{\left|T_k^{\mathrm{in}} - T_k^{\mathrm{out}}\right|^2}} \tag{7}$$

- If mass flow meters are used, $\left\{\mathrm{m}_k^{\mathrm{C}}\left(s_{P,k}\right)\right\}, \left\{\mathrm{m}_k^{\mathrm{D}}\left(s_{P,k}\right)\right\}$: for indirect TES, a sole mass flowmeter, m, is used for charge and discharge:

$$P_k^{\mathrm{C}} = P_k^{\mathrm{D}} = \mathrm{m}_k \left|h(T_k^{\mathrm{in}}) - h\left(T_k^{\mathrm{out}}\right)\right| \tag{8}$$

The fluid enthalpies at the inlet ($h(T_k^{\mathrm{in}})$) and outlet ($h(T_k^{\mathrm{out}})$) are determined according to the procedure described in Annex E, 7.1.2. If the fluid enthalpies are unknown, the according powers at the inlet and outlet can be determined using the specific heat capacity of the fluid according to:

$$P_k^{\mathrm{C}} = P_k^{\mathrm{D}} = \mathrm{m}_k c_p\left(T_k\right)\left|T_k^{\mathrm{in}} - T_k^{\mathrm{out}}\right| \tag{9}$$

For direct TES:

$$P_k^{\mathrm{C}} = \mathrm{m}_k^{\mathrm{C}}\left|h\left(T_k^{\mathrm{in}}\right) - h\left(T_k^{\mathrm{cold\ nom}}\right)\right| \tag{10}$$

$$P_k^{\mathrm{D}} = \mathrm{m}_k^{\mathrm{D}}\left|h(T_k^{\mathrm{out}}) - h(T_k^{\mathrm{cold\ nom}})\right| \tag{11}$$

$$P_k = \mathrm{m}_k \left|h(T_k^{\mathrm{in}}) - h\left(T_k^{\mathrm{out}}\right)\right| \tag{12}$$

The salt enthalpies are determined according to the procedure described in Annex E, 7.1.4. If the salt enthalpies are unknown, the according powers at the inlet and outlet can be determined using the specific heat capacity of the salt according to:

$$P_k^{\mathrm{C}} = \mathrm{m}_k^{\mathrm{C}}\ c_p\left(T_k\right)\left|T_k^{\mathrm{in}} - T_k^{\mathrm{cold\ nom}}\right| \tag{13}$$

$$P_k^{\mathrm{D}} = \mathrm{m}_k^{\mathrm{D}} c_p\left(T_k\right)\left|T_k^{\mathrm{out}} - T_k^{\mathrm{cold\ nom}}\right| \tag{14}$$

$$P_k = \mathrm{m}_k c_p\left(T_k\right)\left|T_k^{\mathrm{in}} - T_k^{\mathrm{out}}\right| \tag{15}$$

If the salt enthalpies are unknown, the uncertainty of the specific heat capacity shall be considered appropriately.

T_k is the average of T_k^{in} and T_k^{out}, that is, $T_k = \frac{1}{2}\left(T_k^{\mathrm{in}} + T_k^{\mathrm{out}}\right)$;

$$s_{P,k} = P_k \sqrt{\left(\frac{s_{\mathrm{m},k}}{\mathrm{m}_k}\right)^2 + \left(\frac{s_{c_p}\left(T_k\right)}{c_p\left(T_k\right)}\right)^2 + \frac{\left(s_k^{\mathrm{in}}\right)^2 + \left(s_k^{\mathrm{out}}\right)^2}{\left|T_k^{\mathrm{in}} - T_k^{\mathrm{out}}\right|^2}} \tag{16}$$

The charge and discharge power curves can be plotted using the corresponding Formula (1) to Formula (11) and from these curves, charge and discharge characteristics and response times can be identified.

Based on the powers calculated in Formula (1) to Formula (11) and including storage system full charge, $t_{\mathrm{full\ charge}}$, and discharge, $t_{\mathrm{full\ discharge}}$, times, the storage system full charge and discharge powers, P_{C} and P_{D}, respectively, can be determined, defined as the average power during full charge or discharge, respectively.

If there are representative numbers M_{C} and M_{D} of measurement points for the charging and discharging, powers $\left\{P_k^{\mathrm{charge}}\left(s_{P,k}^{\mathrm{charge}}\right)\right\}$ and $\left\{P_k^{\mathrm{discharge}}\left(s_{P,k}^{\mathrm{discharge}}\right)\right\}$, it may be assumed that:

$$P_{\mathrm{C}} = \frac{1}{t_{\mathrm{full\ charge}}} \sum_{1}^{M_{\mathrm{C}}} P_k^{\mathrm{charge}} \Delta t = \frac{1}{M_{\mathrm{C}}} \sum_{1}^{M_{\mathrm{C}}} P_k^{\mathrm{charge}} \text{ with } s_{P_{\mathrm{C}}} = \frac{1}{M_{\mathrm{C}}} \sqrt{\sum_{1}^{M_{\mathrm{C}}} \left(s_{P_{P,k}}^{\mathrm{charge}}\right)^2} \tag{17}$$

$$P_{\mathrm{D}} = \frac{1}{t_{\mathrm{full\ discharge}}} \sum_{1}^{M_{\mathrm{D}}} P_k^{\mathrm{discharge}} \Delta t = \frac{1}{M_{\mathrm{D}}} \sum_{1}^{M_{\mathrm{D}}} P_k^{\mathrm{discharge}} \text{ with } s_{P_{\mathrm{D}}} = \frac{1}{M_{\mathrm{D}}} \sqrt{\sum_{1}^{M_{\mathrm{D}}} \left(s_{P_{P,k}}^{\mathrm{discharge}}\right)^2} \tag{18}$$

The powers calculated by Formula (1) to Formula (11) make it possible to know the effective storage capacity, φ, defined as thermal energy, in $\mathrm{MW_t h}$, which the storage system can supply in full discharge from a 100 % storage status.

If during discharge, there are M_{D} representative full discharge powers, $\left\{P_k^{\mathrm{discharge}}\left(s_{P,k}^{\mathrm{discharge}}\right)\right\}$, it may be assumed that:

$$\varphi = \sum_{1}^{M_\mathrm{D}} P_k^{\mathrm{discharge}} \quad \Delta t = \Delta t \sum_{1}^{M_\mathrm{D}} P_k^{\mathrm{discharge}} \tag{19}$$

and

$$S_\varphi = \Delta t \sqrt{\sum_{1}^{M_\mathrm{D}} \left(S_{P_{P,k}}^{\mathrm{discharge}} \right)^2} \tag{20}$$

assuming a negligible error in the time record. Thus, the effective capacity is found in J, ($\varphi|_\mathrm{J}$). If it is desired to express it in $\mathrm{MW_th}$, ($\varphi|_{\mathrm{MW_th}}$), as appears in its definition, the following transformation shall be made:

$$\varphi|_{\mathrm{MW_th}} = \frac{10^{-6}}{3\,600} \varphi|_\mathrm{J} \tag{21}$$

Likewise, since the uncertainty shall be in units coherent with the variable it characterizes, it would have to be:

$$s_\varphi|_{\mathrm{MW_th}} = \frac{10^{-6}}{3\,600} s_\varphi|_\mathrm{J} \tag{22}$$

The storage system's thermal performance, η, is defined as the relationship between energy gained by the heat transfer fluid from the storage system during full discharge and the energy delivered to it by the heat transfer fluid during full charge, E_C, when charge and discharge are consecutive processes. The thermal energy transferred to the system during this full charge, E_C, is calculated by:

$$E_\mathrm{C} = \sum_{1}^{M_\mathrm{C}} P_k^{\mathrm{charge}} \quad \Delta t = \Delta t \sum_{1}^{M_\mathrm{C}} P_k^{\mathrm{charge}} \tag{23}$$

and

$$S_{E_\mathrm{C}} = \Delta t \sqrt{\sum_{1}^{M_\mathrm{C}} \left(S_{P_k}^{\mathrm{charge}} \right)^2} \tag{24}$$

assuming a negligible error in the time record.

The storage system's thermal performance, η, can then be calculated as:

$$\eta = \frac{\varphi|_\mathrm{J}}{E_\mathrm{C}} \tag{25}$$

with

$$s_\eta = \eta\sqrt{\left(\frac{s_\varphi|_\mathrm{J}}{\varphi}\right)^2 + \left(\frac{s_{E_\mathrm{C}}}{E_\mathrm{C}}\right)^2} \tag{26}$$

The associated correction factors, defined in the test procedure, may be applied to these variables, thermal capacity and its uncertainty and thermal performance and its uncertainty, when deviations from nominal are observed in the test conditions. The maximum acceptable deviations in the tests are also defined in the test procedure.

8.2 Thermal losses of the storage system

8.2.1 Test methodology

Thermal losses for the overall thermal storage system shall be evaluated. During testing there shall not be any external thermal energy supply (trace heating, heat elements, boilers, etc.), except for what is necessary to ensure safe functioning of the storage system. The test consists of several stages which are described below:

1) Starting out with the storage system fully charged (100 % storage) at nominal hot tank temperature and volume. Any maximum deviation from nominal shall be agreed upon by the parties in the test procedure. The storage system is fully discharged in an associated time $t_{\text{full discharge}}$, recording the variables as per Clause 6.
2) The thermal energy supplied by the system during this full discharge (nominal capacity expressed in J, ($E_\mathrm{D}|_\mathrm{J}$)) is determined.
3) The storage system is again fully charged to 100 %, reaching the nominal temperature and volume associated with the hot tank at the end of charging. Any possible maximum deviation from nominal shall be agreed upon by the parties in the test procedure.
4) When fully charged, the storage system is maintained without any external energy supply for minimum time, t, of 24 h, acquiring a storage status A of less than 100 %.
5) When time t has passed, it is fully discharged from storage status A with associated time $t_{\text{discharge}}^{A\to 0\,\%}$, recording the variables as per Clause 6.
6) The thermal energy supplied to the system during discharge from storage status A (capacity from status A, E_{D_A}) is determined.

8.2.2 Calculation procedure

Where M_D and $M_\mathrm{D\_A}$ are the numbers of representative power data in the full charge process from storage status A, respectively, we have that

$$E_\mathrm{D}|_\mathrm{J} = \sum_{1}^{M_\mathrm{D}} P_k^{\text{discharge}} \Delta t = \Delta t \sum_{1}^{M_\mathrm{D}} P_k^{\text{discharge}} \tag{27}$$

and

$$s_{E_\mathrm{D}}|_\mathrm{J} = \Delta t\sqrt{\sum_{1}^{M_\mathrm{D}} \left(s_{P_{P,k}}^{\text{discharge}}\right)^2} \tag{28}$$

$$E_{\mathrm{D_A}}\big|_{\mathrm{J}} = \sum_{1}^{M_{\mathrm{D\_A}}} P_k^{\mathrm{discharge}\_A} \Delta t = \Delta t \sum_{1}^{M_{\mathrm{D\_A}}} P_k^{\mathrm{discharge}\_A} \tag{29}$$

and

$$S_{E_{\mathrm{D_A}}}\big|_{\mathrm{J}} = \Delta t \sqrt{\sum_{1}^{M_{\mathrm{D\_A}}} \left(S_{P_k}^{\mathrm{discharge}\_A}\right)^2} \tag{30}$$

So the storage system thermal losses can be calculated as

$$E_{\mathrm{thermal\_losses}} = E_{\mathrm{D}}\big|_{\mathrm{J}} - E_{\mathrm{D_A}}\big|_{\mathrm{J}} \tag{31}$$

where

$$S_{E_{\mathrm{thermal\_losses}}} = \sqrt{(S_{E_{\mathrm{D}}}\big|_{\mathrm{J}})^2 + (S_{E_{\mathrm{D_A}}}\big|_{\mathrm{J}})^2} \tag{32}$$

The associated correction factors, previously defined in the test procedure, may be applied to both thermal losses and their uncertainty, when deviations from nominal are observed in the test conditions. The maximum deviations in these test conditions shall also be defined in the test procedure.

8.3 Global energy losses of the storage system

8.3.1 General

This test should be performed only if it has been so agreed in the test procedure.

8.3.2 Test methodology

During testing there shall be no external thermal energy supply (heat tracing, heating elements, boilers, etc.), except what is necessary to ensure safe functioning of the storage system. The overall thermal storage system energy loss test consists of several steps which are described below:

1) Starting out from the fully discharged storage system (0 % storage), the storage system is fully charged to nominal hot tank temperature and status, with an associated time $t_{\text{full charge}}$. Any maximum deviation from nominal shall be agreed by the parties in the test procedure, recording the variables as per Clause 6. Before charging, it is recommended that the whole storage system be preheated to a temperature as close as possible to the one specified by the operating procedures, and this situation shall be verified by measuring the temperature at several different points in the system, as specified in Clause 6.
2) Thermal energy transferred to the system during this full charge period, E_{C}, is determined.
3) When fully charged, the storage system is maintained, with no external energy supply, for a minimum time t of 24 h, acquiring a storage status A of less than 100 %.
4) The system is fully discharged from storage status A down to 0 % with an associated time $t_{\mathrm{discharge}}^{A \to 0\ \%}$ recording the variables as per Clause 6 with no external energy supply.
5) The thermal energy supplied by the system during the period of discharge from status A (capacity from status A, E_{D_A}) is determined.

8.3.3 Calculation procedure

Where M_C and $M_\mathrm{D\_A}$ are the numbers of representative power data in full charge and full discharge from storage status A, respectively, we have that

$$E_\mathrm{C} = \sum_{1}^{M_\mathrm{C}} P_k^\mathrm{charge} \Delta t = \Delta t \sum_{1}^{M_\mathrm{C}} P_k^\mathrm{charge} \tag{33}$$

and

$$S_{E_\mathrm{C}} = \Delta t \sqrt{\sum_{1}^{M_\mathrm{C}} \left(S_{P_k}^\mathrm{charge} \right)^2} \tag{34}$$

$$E_{\mathrm{D_A}}\big|_J = \sum_{1}^{M_\mathrm{D\_A}} P_k^{\mathrm{discharge}\_A} \Delta t = \Delta t \sum_{1}^{M_\mathrm{D\_A}} P_k^{\mathrm{discharge}\_A} \tag{35}$$

and

$$S_{E_{\mathrm{D_A}}}\big|_J = \Delta t \sqrt{\sum_{1}^{M_\mathrm{D\_A}} \left(S_{P_k}^{\mathrm{discharge}\_A} \right)^2} \tag{36}$$

The overall storage system losses can be calculated by

$$E_\mathrm{overall\_losses} = E_\mathrm{C} - E_{\mathrm{D_A}}\big|_J \tag{37}$$

where

$$S_{E_\mathrm{overall\_loss}} = \sqrt{\left(S_{E_\mathrm{C}} \right)^2 + \left(S_{E_{\mathrm{D_A}}}\big|_J \right)^2} \tag{38}$$

The associated correction factors, previously defined in the test procedure, may be applied to both overall energy losses and their uncertainty, when deviations from nominal are observed in the test conditions. The maximum deviations in these test conditions are also defined in the test procedure.

9 Verification procedure

The implicit purpose of thermal storage system feature quantification tests is to compare the values found in testing with the guarantee or reference values given in the test procedure. For this, it should be taken into account that both the values found in the tests and the reference values are subject to uncertainty, so treatment of uncertainties in the verification procedure is critical.

The expanded uncertainty (Δx) provides an interval about the measurement, x, which contains most of the distribution of values which could reasonably be attributed to the measuring. It is calculated by multiplying the combined standard uncertainty of the variable measured, s_x, by a coverage factor, FC, whose value is based on the probability or level of confidence required for the interval in accordance with Table 3 of this document and with ISO/IEC Guide 98-3:2008. The level of confidence, and therefore, the coverage factor, shall be agreed upon by the parties for verification of the features. The verification procedure shall consist of comparing the reference and/or guarantee value with the one found during testing, taking its corresponding uncertainties into account. The criterion for comparison shall be defined in the test procedure.

See Table 3 for levels of confidence and associated coverage factors.

Table 3 – Levels of confidence and associated coverage factors (Gaussian distribution)

Level of confidence %	**Coverage factor** FC
68,27	1
90	1,645
95	1,960
95,45	2
99	2,576
99,73	3

Since this point is considered critical, the following concepts shall be defined clearly in the test procedure:

- Combined standard uncertainty associated with the reference value (s_{x_Ref}). The reference value, x_{Ref}, shall be found preferentially from the simulation model, and may be used as the feature guarantee value, and if it is provided, the procedure followed to arrive at that value should be explained.
- Level of confidence and coverage factor (FC) to be applied to determine the expanded uncertainty (Δx) of the value found in testing, x, based on the combined standard uncertainty, by Δx = FC·s_x. If it is decided to include the expanded uncertainty of the value of reference (Δx_{Ref}), it shall be found the same way.

Two possible comparisons are given below as examples:

Case a): It is agreed that the minimum representative measurement, x, according to its uncertainty band or expanded uncertainty, Δx, is above the reference value, x_{Ref}, with its uncertainty band, Δx_{Ref} (Figure 4 a):

$$(x-\Delta x) > (x_{\text{Ref}} + \Delta x_{\text{Ref}}) \tag{39}$$

where $\Delta x = FC_x s_x$ and $\Delta x_{\text{Ref}} = FC_{x\text{Ref}} s_{x\_\text{Ref}}$

where

FC_x is the coverage factor agreed for variable x,

$FC_{x\text{Ref}}$ is the coverage factor agreed for reference value x_{Ref},

s_x is the combined standard uncertainty of variable x,

s_{x_Ref} is the combined standard uncertainty of the reference value x_{Ref}.

Case b): It is agreed that the representative value of the measurement, considering its uncertainty band, is within the uncertainty band of the reference value (Figure 4 b):

$$(x + \Delta x) > (x_{\text{Ref}} - \Delta x_{\text{Ref}}) \tag{40}$$

See example criteria in Figure 4.

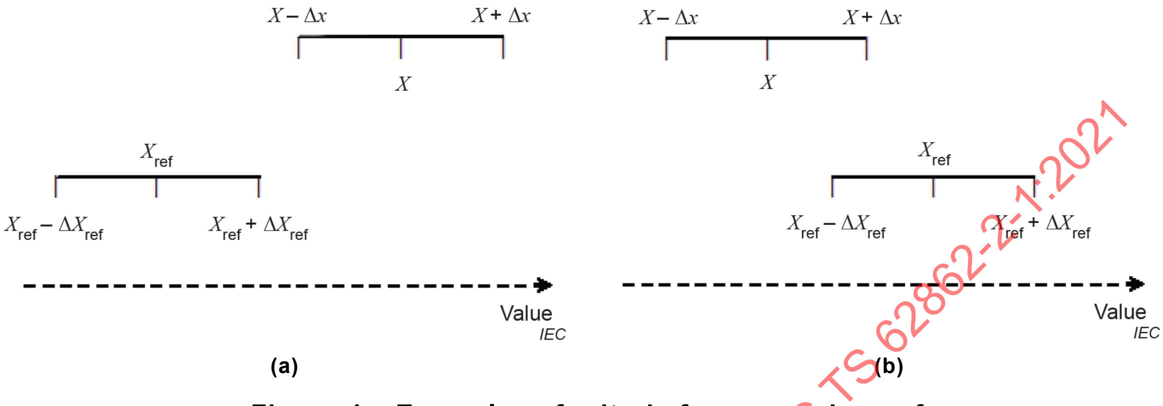


Figure 4 – Examples of criteria for comparison of the measurement (M) and the reference value (RV)

As explained above, the criterion for comparison of features should be set in the test procedure.

10 Test report (results)

The test report, which is written at test completion, shall contain, as a conclusion, the results of tests and their analysis.

The final report including the test results shall include detailed information as follows:

- introduction,
- description of the tests done,
- instrumentation methodology,
- measurements,
- calculations and results analysis,
- conclusion,
- reference documents,
- datasheet of each test.

The contents of the report shall be structured in accordance with Annex E.

Annex A
(informative)

Thermal energy storage system types

A.1 Thermal energy storage modes

A.1.1 General

Thermal energy storage can be classified either by its mode, configuration, or fluid circulation.

Thermal energy supplied by the solar field may be stored as sensible heat, latent heat, reaction heat or a combination of them.

- Storage as sensible heat involves a change of temperature in the storage medium and can be carried out using solid or liquid media or a combination of both (dual medium).
- Storage as latent heat, also called phase-change, involves a state change in the storage medium and can be carried out using any phase transition: solid/solid, solid/liquid, liquid/liquid, liquid/vapour or solid/vapour.
- Storage as reaction heat involves a change in the composition of the storage medium due to a chemical reaction.

TES systems are classified as:

- sensible heat storage,
- latent heat storage, and
- thermochemical energy storage.

A.1.2 Sensible heat storage

Sensible heat storage systems achieve storage by raising the temperature of a medium; therefore, the sensible storage materials undergo no change in phase over the temperature range of the storage process. Sensible heat storage in a material depends strongly on its heat capacity, which determines the energy density and the thermal diffusivity, which determines the rate at which that heat can be released and extracted.

The amount of energy stored is given by the following equation:

$$Q = m\, C_p\, \Delta T \qquad (41)$$

where

Q is the energy stored;

m is the mass of the storage medium;

C_p is the specific heat of the material; and

ΔT is the temperature change during the process.

All of the TES systems currently installed in utility-scale solar thermal electric plants store energy using sensible heat.

A.1.3 Latent heat storage

The latent heat storage systems utilize materials that change phase at a temperature that falls within the upper and lower limit of the solar field. In doing so, they exploit the latent heat, or enthalpy, associated with phase transition. Phase change phenomena vary from solid-solid, liquid-vapour and solid-liquid transitions, however the latter is typically used owing to its low volumetric expansion compared to the liquid-gas transition and owing to its high latent heat compared to the solid-solid transition.

The energy stored in mass m for a solid-liquid transition in a phase change material (PCM) is

$$Q = m \left[c_{p_s} (T_m - T_s) + h + c_{p_l} (T_l - T_m) \right] \tag{42}$$

where

c_{p_s} is the average specific heat in the solid phase;

c_{p_l} is the average specific heat in the liquid phase;

h is the enthalpy of phase change;

T_m is the melting temperature;

T_s is the temperature of the solid; and

T_l is the temperature of the liquid.

A.1.4 Thermochemical energy storage

The thermochemical storage systems rely on heat from the solar field to drive reversible chemical reactions, thus the storage medium shall have the ability to completely dissociate in the temperature range of the solar field. In this storage concept, the reaction in the forward direction is endothermic while the reverse reaction is exothermic. The amount of heat stored in a chemical reaction depends on the heat of reaction and the extent of conversion given by:

$$Q = a_r \, m \, \Delta H \tag{43}$$

where

a_r is the fraction reacted; and

ΔH is the heat of reaction per unit mass, m.

A.2 TES configuration

Thermal energy storage technologies are also classified in terms of applied process and loading method meant to direct thermal storage and indirect thermal storage.

- Direct: when the heat transfer fluid circulating through the solar field and other plant systems is also used as the storage medium.
- Indirect: when the storage medium is different from the heat transfer fluid circulating through the solar field and other plant systems.

A.3 Circulation of the storage medium

Solar thermal power plant storage systems may be classified by circulation of the storage medium:

- Active systems: when the storage medium is circulated through the storage system.
- Passive systems: when the storage medium does not circulate.

When the storage medium is a fluid and is able to flow between the tanks, the systems are referred to as active type systems. If the storage medium is also used as the heat transfer fluid, the system is referred to as a direct-active system. An additional heat exchanger is needed when the storage fluid and heat transfer fluid are different and the unit is referred to as an indirect-active type. In cases where the storage medium is solid, the HTF passes through the storage material only for charging and discharging. Such a system is called a passive type.

In an active storage system, the storage material itself circulates between the heat exchangers for energy transfer. The employed heat exchangers can also be solar receivers or steam generators.

In passive storage systems, the HTF carries energy received from the energy source to the storage medium during charging and receives energy from the storage system when discharging (these systems are also called regenerators). The arrangement for the HTF to flow through the storage medium is a major parameter that dictates heat transfer in the unit. When the heat transfer fluid is a liquid and the heat capacity of the solid in the storage system is not negligible, the system is called a dual storage system. Passive storage systems may utilize solids such as rocks, sand or concrete for sensible heat storage materials, or phase change materials for storing thermal energy.

Annex B
(informative)

Description of the main components of the active direct/indirect TES using molten salts

B.1 Storage media

At the time of publication of this document, the molten salts are usually a mixture of KNO_3 and $NaNO_3$ close to the eutectic point and have a purity higher than 99 %.

The nominal composition of the molten salt is approximately 60 % by weight $NaNO_3$ and 40 % by weight KNO_3 in order to minimize the mixture solidification temperature.

The limits for the nitrate salt concentration are around:

- $NaNO_3$: minimum 59 % by weight; maximum 61 % by weight;
- $KNaO_3$: minimum 39 % by weight; maximum 41 % by weight.

The maximum contamination from all sources shall be:

- Chloride ion from all sources: 0,21 % (by weight);
- Nitrite: 1 % (by weight);
- Carbonate: 0,1 % (by weight);
- Sulfate: 0,75 % (by weight);
- Hydroxyl alkalinity: 0,2 % (by weight);
- Perchlorate: 0,25 % (by weight);
- Magnesium: 0,05 % (by weight).

The maximum molten salt temperature in any working condition, including in any transient condition or any ambient condition, shall be such as to avoid any degradation or evaporation of the molten salt or damage to the molten salt system components.

The minimum molten salt temperature in any working condition, including any transient condition or any ambient condition, shall be 10 K above the starting of molten salt crystallization/solidification.

B.2 Tanks and foundation

B.2.1 Tanks

Design shall, at a minimum, follow typical design standards, such as API or EN 14015. Tanks shall be dimensioned to minimize heat loss surface.

Tanks shall be insulated on all sides. Special care shall be taken with insulation to the ground as part of the foundation design. No heat exchange and losses may appear to ground water or aquifers below the tank.

MSF tanks shall be provided with a suitable heating system. This system shall keep the temperatures in the tanks at a suitable protection level against solidification. If necessary, a mixer should be provided in each tank. Auxiliary heater or heater systems shall be designed to provide heat for the protection of the MSF system against solidification. Efficiency of any auxiliary heater shall be superior to 80 %.

MSF tanks shall be located in a proper containment area. The containment area can be a basin or with dams and shall be able to collect the full amount of MSF in case of leakage.

Tanks shall be provided to sustain the dead load of the tank in conjunction with the filling and emptying and store loads associated with tank contents.

Bolted tanks shall not be used as process tanks. All tanks are designed and installed based on local and international codes and standards for pressure and servicing requirements.

Tank sizes shall include the necessary volume to ensure that there is adequate net positive suction head required by the associated pumps plus minimum suction entry clearances as recommended by the pump manufacturer.

Tank manholes shall have a minimum of 600 mm diameter.

The hot tank, in the case of indirect storage, shall have a slight nitrogen pressure to ensure the blanketing in the system.

B.2.2 Foundations

The foundations of the molten salt storage tanks and overflow tank shall be designed and constructed taking into account the high temperatures, high load and changes in load and soil conditions.

The foundation of the molten salt storage tanks shall take into account the maximum allowable temperature of the foundation materials.

B.2.3 Insulation

Thermal insulation shall be provided as appropriate to conserve energy, provide protection to personnel, provide freeze protection, prevent condensation, and attenuate noise. Insulation materials to be used in points of potential HTF leaks shall be properly selected.

Insulation design and materials shall be in accordance with internationally recognized standards and shall contain neither sulphur compounds nor asbestos.

Insulation and lagging shall be provided with an adequate inspection window for thickness measurement, particularly at pipe bends or tanks.

For safety reasons and in order to avoid injury to persons, other protection measures may be taken in areas where contact with lagging is possible.

The required thickness of insulation shall be such that the surface temperature of the lagging shall not exceed 55 °C when measured in an ambient air temperature of 30 °C with under 0 m/s wind speed.

B.3 Materials

As the corrosion values depend on the fluid type, and on operating conditions (mainly temperature), and on base material grades, the corrosion allowances shall be defined on a case by case basis, applicable to all piping, tanks, pressure vessels and all other surfaces in contact with MSF.

The TES system shall not be designed with materials that are incompatible with molten salt systems, for example graphite seals.

B.4 Piping

The MSF piping shall be able to be fully drained by gravity. Molten salt shall not be accumulated at any low point in the piping installation.

The piping slope shall be maintained under all thermal expansions and conditions to allow for gravity draining.

Piping connections shall be welded. Flanged connections shall be with ring type joint type.

All flange gaskets/rings used for molten salt flow shall be MSF compatible.

Butt weld fittings shall be used for all Nominal Pipe Sizes (NPS), even for 5,08 cm (2 in) and lower nominal diameters. Socket welded connections shall not be used.

Salt interconnecting piping shall be fully heat traced and insulated. All piping systems shall be properly sloped to be drained if necessary.

B.5 Pumps

The pumps shall be of the vertical type with an extended shaft which is mounted on a platform above the tank. The pumps' structural support shall take into account the transmission of vibrations.

The structural support frame shall allow the operator access for any maintenance activity.

As a minimum, the pumps shall comply with the following requirements:

- Pumps shall be self-draining, if applicable.
- Pumps shall be grease or oil lubricated and have a replaceable thrust bearing.
- Pumps shall be submerged and have salt lubricated radial bearings.
- Pumps shall be provided with a seal system in order to avoid leaks; seal systems shall be able to drain molten salts into the tanks.
- Redundancy requirements shall be analysed on a case by case basis.
- Pumps shall possess adequate allowances for relative thermal growth among shafts, impellers and bowls. Pumps shall have axial adjustments and possess good heat dissipation characteristics.
- Pump discharge heads shall be electric heat traced (EHT) and insulated to allow the thermal condition to be maintained and prevent the salt from freezing.
- Pumps shall take in to account the transmission of vibration to the pipes.
- Pumps shall be equipped with temperature and vibration sensors.
- Pump shaft height shall be in accordance with the total tank height and the minimum volume to be contained in the molten salt tanks.
- The outlet of the molten salt pumps shall have a drain line to allow the complete drainage of the outlet lines.

B.6 Heat exchanger

The HTF/MSF heat exchangers shall be designed, constructed and tested in accordance with internationally recognized standards such as the ASME Boiler and pressure vessel code, Section III and VIII, TEMA and HEI standards. The HTF/MSF heat exchangers shall be placed over a retention basin.

The support frame shall allow for the thermal expansion of the components minimizing the forces and moments over the HTF/MSF heat exchanger.

The HTF/MSF heat exchangers' design shall take into account the thermal stress due to a quick change of the temperature during start-up.

The heat exchanger shall be insulated to minimize heat loss and to avoid draining during short stand-still periods.

B.7 Safety and control system

B.7.1 General

The TES system shall include, at a minimum, the following safety systems: blanketing system for tanks, blanketing system for heat exchangers (for indirect systems), leak detection (including leaking of HTF into MSF), firefighting system (if required by international firefighting codes or local authorities), freeze protection system, instrumentation, thermal insulation.

B.7.2 HTF and MSF leak detection system

The HTF and MSF leak detection system, in the case of indirect TES, shall have the following functions:

- detect a leak as soon as it occurs;
- in the case of indirect TES, separate the HTF present in the MSF circuit;
- in the case of indirect TES, the HTF and MSF leak detection system shall consist of two types of detection.

Pressure gauges are installed between the exchangers to detect possible HTF leaks due to a rapid pressure increase.

B.7.3 Instrumentation

Tanks shall be equipped with a suitable level control system. A mechanical level indicator is not accepted as a single indicator.

The tanks shall be equipped with a suitable setting of temperature controls and indicators at several levels, to always allow control of the temperature levels of the MSF in the tank.

B.7.4 Freeze protection system

B.7.4.1 General

The MSF, which is used to store energy, has a freezing point of about 238 °C. For this reason, it is important to provide the TES with a freeze protection system to keep the salt temperature above the melting temperature.

For this purpose, the following levels of protection may be applied:

- recirculation of salts.
- electrical heat tracing system: all piping, drainage tank and heat exchanger components shall be electrically traced.
- electric heaters submerged in the dead space at the bottom of the hot and cold salt tank.

B.7.4.2 Recirculation of salts from/to the same tank

The main purpose of the recirculation system is the homogenization of the temperature of the salts. The recirculation system enables the salts to be recirculated from a tank to the same tank or through the heat exchangers, during the storage waiting hours.

The recirculation system enables the compensation of heat losses through the circulating in the heat exchangers of a small amount of HTF if it is available (recirculation through heat exchangers) or, if not, the compensation of heat loss is achieved by means of the electric heaters of the tanks (recirculation over tanks).

B.7.4.3 Recirculation through exchangers

This option is provided mainly to avoid a salt solidification in heat exchangers and in the interconnecting pipes. This entails recirculation using cold pumps through exchangers and return to the cold salt tank to compensate for heat losses of the lines. It is necessary to circulate the amount of HTF required in an adequate temperature, i.e., a temperature that is high enough to prevent the salt from freezing. Recirculation may be carried out through the exchangers when the operator deems it necessary, by activating this option in normal mode.

B.7.4.4 Recirculation over tanks

This option is provided to protect the lower layers of the tank from freezing and avoid stratification of the molten salts inside the tank, so that a homogenous temperature in the whole tank is kept. This entails recirculation over tanks using one (1) or two (2) pumps at minimum revolutions without passing through the exchangers. The molten salts leave the tank and return to the same tank. Recirculation over tanks may be carried out both in the cold salt tank and in the hot salt tank. Recirculation may be carried out over the tanks when the operator deems it necessary by activating this option in normal mode.

B.7.4.5 Electrical heat tracing system

The heat exchangers, the drainage tank, the salt pumps, valves and the piping of the TES have electric heat tracing to prevent the salts from freezing. This tracing is activated automatically when the surface temperature sensors of the equipment detect a temperature below the value at which the risk of freezing is high; alternatively, the tracing is activated manually by the operator.

The temperature on the surface of materials/equipment should be monitored continuously in each section, with a low temperature alarm. If required, the system shall be connected to the emergency services network that receives auxiliary power from an emergency diesel generator. This electric heat tracing system will essentially consist of an electrical resistor inserted into a metal sheath, temperature sensors and controllers. The system will be integrated into the distributed control system of the plant.

B.7.4.6 Electric heaters

To prevent the salts from freezing during long plant shutdown periods, each tank (the cold salts storage tank and the hot salts storage tank) shall be provided with heaters, typically electrical ones, placed in the dead space at the bottom of the tank.

These electric heaters are to compensate the heat lost through the walls and the bottom of the tank and shall be installed in sheaths so that they can be removed without emptying the tank.

If the temperature in the tank drops to a value at which the risk of freezing is high, the heaters will be turned on according to the situation. In addition, they will be equipped with high temperature shutdown and low liquid level.

The first phase of filling the tanks is the most critical. To activate the heaters, it is necessary that they be covered with salts, because otherwise the sheathing of these resistors would quickly reach the trigger temperature (i.e., the temperature at which the resistor could be damaged if there is not enough salt). A gas burner may be used to replace the thermal energy dissipated into the system to prevent freezing of the salts below this level.

When the salts have arrived in the cold tank and they reach the appropriate level where the electric heaters are located, the resistors at the bottom will be turned on to ensure the permanence of the salts in molten state and to compensate the heat loss.

The tanks shall be equipped with immersion heaters located below the minimum salt level. The redundant electric heaters make sure that the salt temperature is maintained above its freezing point.

The immersion heaters extend radially within the interior of the tanks. The heaters are contained in dedicated capped pipes, which are attached in the correct manner to the tanks. The heaters can be extracted from the tanks' side walls in case replacement is needed.

B.7.5 Molten salt valves

Bonnet extension is required with sufficient stand-off distance from the high temperature salt.

B.7.6 Blanketing system

In the case of indirect TES, the nitrogen atmosphere is necessary to ensure that no oxygen is present in the event that there is HTF in any of the tanks due to a rupture of one of the exchanger tubes.

A nitrogen supply will be provided for the following main functions:

- maintain the salts storage tanks, hot and cold tanks, and the drainage tank inert.
- nitrogen supply to the heat exchanger system for inerting and pressurizing the line and facilitating the pumping of salts from the cold tank.
- availability of working fluid for level measuring instruments in the salt storage tanks.
- salt drainage coming from the exchangers and their corresponding lines
- nitrogen for hydrocarbon analysis, if required depending on the analysis method.

B.7.7 Welding of the control system

All welding shall be in accordance with the appropriate international standard.

All shop and field welding procedures shall be in accordance with the appropriate international standard. Welders and operators of machine welding equipment for welding of pressure parts shall be qualified in accordance with internationally recognized standards such as with the latest edition of the ASME Boiler and Pressure Vessel Code, Section IX, "Welding, Brazing and Fusing Qualifications" or equivalent.

The extent of weld inspection and the final weld quality shall comply with the applicable codes and standards. Records of all welder qualifications, weld procedures, and weld inspection and repair reports shall be maintained and made available on request.

Welders with all necessary training and qualification shall be employed in permanent positions and remain on site for the maintenance of the plant.

B.8 Melting system

The salts are supplied in the solid form and then shall be melted before startup of the plant.

The salts shall be dosed in the solid state in the appropriate mixture and with an adequate grain size, in order to facilitate fusion and avoid downtime.

The melting unit is composed of solids handling equipment and a melting furnace.

The melting process shall be started once all equipment involved in the molten salt operation is prepared and is without anomalies, including but not limited to the preheating of the cold salt tank and the lines involved during the filling of the cold salt tank.

The transfer of the salts to the tank is carried out via vertical pump located in the melting furnace. The discharge rate of the melting furnace to the cold tank shall vary during the start-up or in the presence of anomalies in the process. These flow rate variations will entail a control valve modulation which shall ensure a consistent average level in the tank. This average is defined in order for there to be a volume available for the return of the salt contained in the line toward the tank, in case of a power failure.

At the beginning of the fusion, the whole amount of the salts shall be introduced to the cold salt tank. There are three different phases during the filling of the cold salt tank:

- Minimum level for the start-up of the pumps: For the start-up of the pumps, a minimum salt level shall be reached. Once this level is reached, the recirculation of the salts may be carried out using one of the cold salt pumps.
- Submergence of the electric heaters: To activate the heaters, it is necessary that they be covered with salts, because otherwise the sheathing of these resistors would quickly reach the trigger temperature (i.e., the temperature at which the resistor could be damaged if there is not enough salt). The temperature probes of the heaters shall thus be operational.
- Fusion and filling completion: Once the inventory of salts is melted, the fusion and tank filling process can be considered complete.

Annex C
(normative)

Data acquisition and treatment

C.1 Flow signal measurement

To measure the flow, at least two independent flow meters are required, located before and/or after the storage system, maintaining minimal installation conditions required by the manufacturer for reliable measurement.

Therefore, at least the two following experimental instantaneous data series shall be kept[2] $\left\{\overset{*}{q}_{1,\mathrm{j}}\left(\overset{*}{s}_{q1}\right)\right\}$ and $\left\{\overset{*}{q}_{2,\mathrm{j}}\left(\overset{*}{s}_{q2}\right)\right\}$.

The uncertainties considered here, $\overset{*}{s}_{q1},\overset{*}{s}_{q2}$, are the device and the data acquisition system, that is, Type B uncertainties.

Measuring for at least 10 minutes means that a minimum of 10 data points shall be recorded[3], ($N \geq 10$). Thus knowing that there are n_q flow meters ($n_q \geq 2$), at least the following data series shall be recorded: $\left\{q_{1,k}\left(s_{q1,k}\right)\right\}$ and $\left\{q_{2,k}\left(s_{q2,k}\right)\right\}$

where,

for i = 1:n_q $\quad q_{i,k}=\frac{1}{N}\sum_{\mathrm{j}=1}^{N}\overset{*}{q}_{i,\mathrm{j}}$ and $s_{qi,k}=\sqrt{\frac{1}{N-1}\sum_{\mathrm{j}=1}^{N}(\overset{*}{q}_{i,\mathrm{j}}-q_{i,k})^2+(\overset{*}{s}_{qi,\mathrm{j}})^2}$

since it considers both the experimental standard deviation (dispersion around the mean, i.e. first term in the root) and Type B variance (second term in the root).

ISO 5725-3 and ISO 5725-6 are applied for a single representative volumetric flow rate value at each recording time and thereby have the resulting series $\left\{q_k\left(s_{q,k}\right)\right\}$ based on the above-mentioned data series.

2 One way recommended by ISO/IEC GUIDE 98-3:2008 for expressing a measurement and its uncertainty is to place the measurement (followed in parentheses by the numerical value of the combined standard uncertainty) expressed in the corresponding units. This way, the symbol "±", which is usually associated with a confidence interval, is avoided.

3 According to the central limit theorem, 10 is the minimum number to be averaged so that the resulting average has a distribution similar to that of the unmeaned values.

For the flow, the mean, $\overline{q_k}$, is calculated by

$$\overline{q_k} = \frac{1}{n_q} \sum_{i=1}^{n_q} q_{i,k} \tag{44}$$

The standard uncertainty (estimate of standard deviation), $s_{q,k}$, is calculated by

$$s_{q,k} = \sqrt{\sum_{i=1}^{n_q} \left(s_{qi,k}\right)^2} \tag{45}$$

The critical range factor, $f(n_q)$ [4], is given by the number of sensors, n_q, as per Table C.1.

Table C.1 – Critical range factor, $f(n_q)$, depending on the number of sensors, n_q, available

n_q	2	3	4	5	6
$f(n_q)$	2,8	3,3	3,6	3,9	4,0

In the case of flow rate measurements, $n = n_q \geq 2$:

- if $\max\left(\left\{q_{i,k}\right\}_{i=1:n_q}\right) - \min\left(\left\{q_{i,k}\right\}_{i=1:n_q}\right) \leq f\left(n_q\right) \times s_{q,k}$ then, $q_k = \overline{q_k}$;
- if $\max\left(\left\{q_{i,k}\right\}_{i=1:n_q}\right) - \min\left(\left\{q_{i,k}\right\}_{i=1:n_q}\right) > f\left(n_q\right) \times s_{q,k}$ then $q_k = \text{median}\left(q_k\right)$.

Table C.2 shows an example of how flow rate (volumetric) measurements would be treated.

Although it is less usual, the heat transfer fluid flow may be measured by a mass flow meter in kg/s. In this case, at least two devices are required to measure the flow rate, and the procedure for calculating a single representative mass flow rate data series $\left\{m_k\left(s_{m,k}\right)\right\}$ is similar to that described above for the volumetric flow rate.

[4] The critical range factor, $f(n)$, defines a confidence level of 95 % of the distribution, corresponding to a sample size with n data, assuming normal distribution.